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14. ABSTRACT

A study has been made of how the physical properties of the liquid propellants hydrazine and hydrogen peroxide influence energy conversion device dimensions across multiple operating configurations. The energy conversion device was a staged rocket thruster comprised of a first stage where propellant is decomposed to create a high temperature, low velocity environment and a second stage downstream where propellant is injected and exothermically decomposed. The operating configurations varied chamber pressure, propellant flow rate ratio of first stage to second stage, and ratio of propellant feed pressure to chamber pressure within the thruster. Chamber pressures of 125, 250, and 500 psi; flow rate ratios of 1:3, 1:4, and 1:5; and feed to chamber pressure ratios of 1.25:1 and 1.75:1 were considered. The study utilizes relationships that were empirically derived to estimate droplet sizes as a function of the propellant physical properties and various related operating conditions. As the chamber pressure and feed to chamber pressure ratio increased, the chamber dimensions decreased. As the flow rate ratio decreased, the chamber length increased. Relative to the primary reference, Ryan, instant study theoretical values achieved were consistently 30-50% low. Contributing to the disagreement, was use of injector orifice diameters below those of the reference which would drive increased injection velocity values and drive the results lower.

15. SUBJECT TERMS

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CALIFORNIA STATE UNIVERSITY, NORTHRIDGE

Impact of Liquid Propellant Properties on Small Rocket Thruster Dimensions

A thesis defense submitted in partial fulfillment of the requirements
For the degree of Master of Science in Engineering

By

Anthony Zuttarelli

May 2012

Impact of Liquid Propellant Properties on Small Rocket Thruster Dimensions

- **Objective**

- **Section 1: Introduction**
  - Background
  - Configuration
  - Physical Process
  - Propellants
  - Investigation Constraints and Presumptions

- **Section 2: Approach and Analysis**
  - Discussion of References
  - Analytical Process

- **Section 3: Results and Discussion**

- **Section 4: Summary and Conclusions**

- **References**

- **Nomenclature**

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The objective of this study was to develop the relationships required to estimate small rocket thruster dimensions over a range of operating conditions as a function of the liquid propellant properties of viscosity, surface tensions, and density.

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- **Alternative fuel/propellant sources being sought that are:**
  - **Less environmentally impactful**
  - **Renewable**
  - **Can be easily implemented into today's infrastructure**

- **Fuel/Propellant candidates that meet these criteria will most likely have different formulations than those that are the state of the art in common use**
  - **Formulation changes can drive changes in energy conversion devices in common use**
    - **Estimation of the delivered performance prior to empirical development reduces the cost implementation**

- **The instant study considers how the changes of a liquid propellant's physical properties can impact the dimensions of an energy conversion device**
  - **In this case study, for a spacecraft thruster**
  - **Hydrazine, N_2H_4, and hydrogen peroxide, H_2O_2, are contrasted**
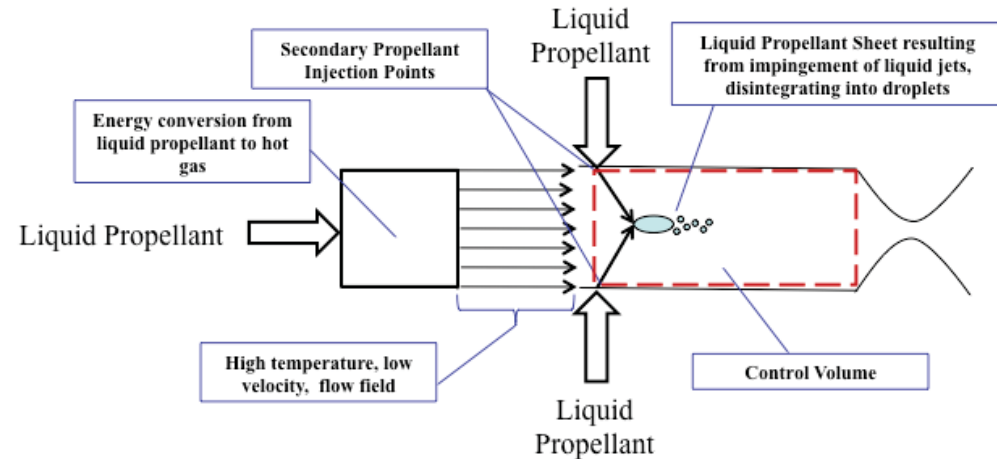
- A two-stage rocket thruster configuration was used in the study
  - 5 lb$_f$ (22 N) thrust parameter was set
    - Used to set the overall mass flow rate
  - Propellant is injected in two locations
    - First stage-some fraction of propellant is injected into an ignition/decomposition device
    - Second stage-remainder of propellant is injected downstream into the high temperature, low velocity gas flow
      - Two impinging streams that impact and atomize into droplets
      - The high temperature environment prompts the droplets to convert from liquid phase to decomposed gas phase

Secondary Propellant Injection Points

Liquid Propellant

Liquid Propellant Sheet resulting from impingement of liquid jets, disintegrating into droplets

Energy conversion from liquid propellant to hot gas

Liquid Propellant

High temperature, low velocity, flow field

Control Volume

Liquid Propellant

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- Two stage thruster configuration dimensions are driven by multiple physical processes
  - Stage 1: Propellant decomposition to form a high temperature, low velocity environment
    - Propellant decomposition/ignition means is presumed to be a catalytic reactor
      - Technology is established and flight proven
    - The decomposition species and gas temperature exiting and propellant mass flow rate into the decomposition/ignition means are tracked
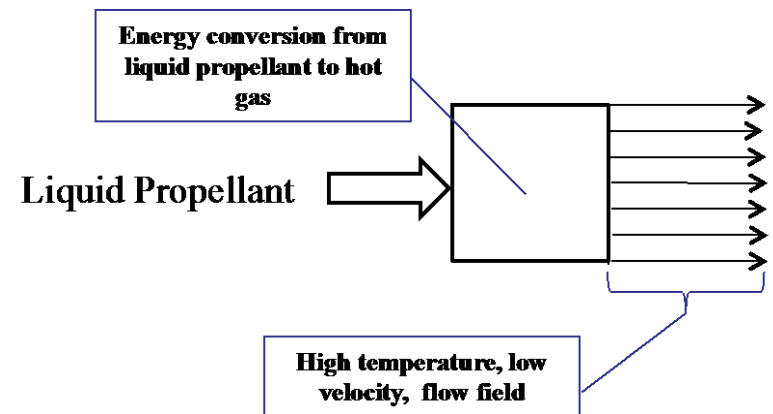
Stage 1: Propellant Decomposition/Ignition

- Decomposition species knowledge is relevant to determining environmental parameters
  » specific heat ratio & heat transfer coefficients
- Gas temperature is derived from specific impulse calculations and inputted into relations
- Propellant mass flow rate into the decomposition/ignition means drives atomization properties of the second stage
  - Propellant reaction kinetics and species properties are primary configuration drivers from this stage
    - Establishes the environment that liquid propellant is injected into and atomized within
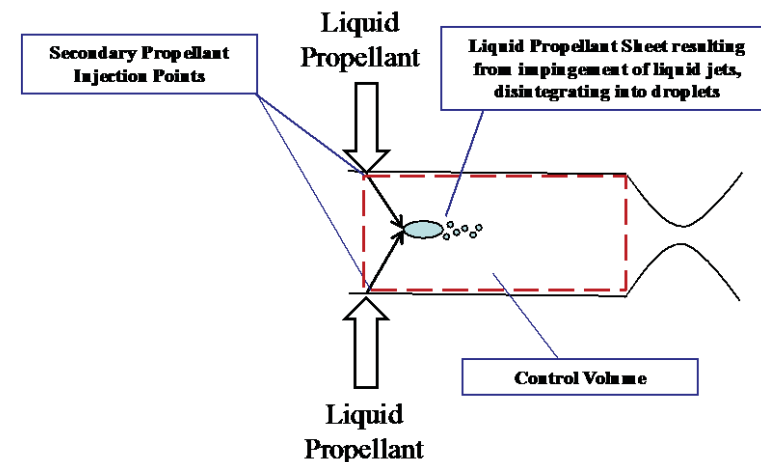
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- **Two stage thruster configuration is driven by multiple physical processes**
  - **Stage 2: Downstream Propellant injection**
    - **Propellant is injected as two impinging streams**
      - **Impinging streams form a liquid sheet which then deteriorates into ligaments, then droplets**
    - **Propellant physical properties of density, viscosity, and surface tension; configuration parameters of injector orifice diameter and injection velocity are the primary chamber length impacts in the relations governing the second stage**

Liquid Propellant

Secondary Propellant Injection Points

Liquid Propellant Sheet resulting from impingement of liquid jets, disintegrating into droplets

Control Volume

Liquid Propellant

Stage 2: Propellant Atomization

Ligaments

x_b

Impingement point plane

2θ

ϕ r_L
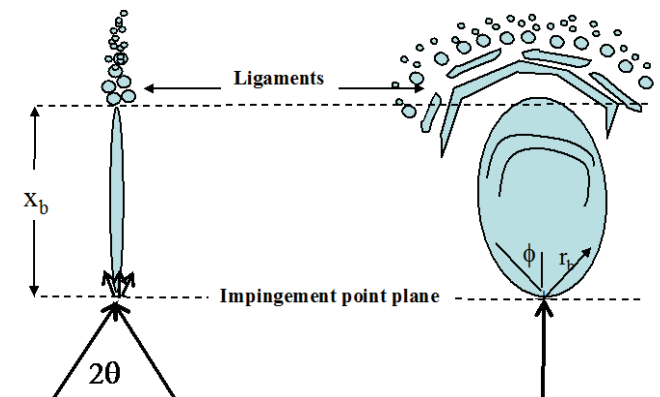
Liquid Sheet Deterioration to Droplets
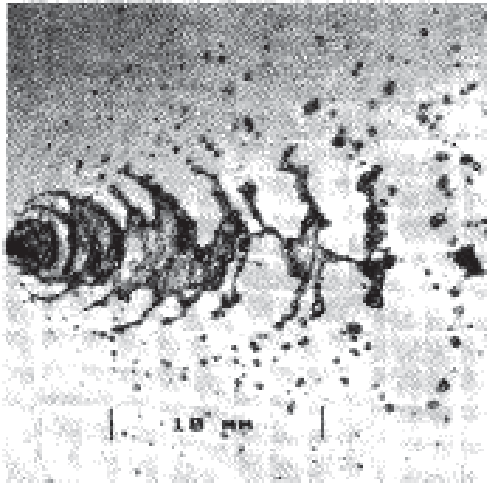
Low jet velocity (6.4 m/s) turbulent impingement sheet photo (figure 3a from Ryan)
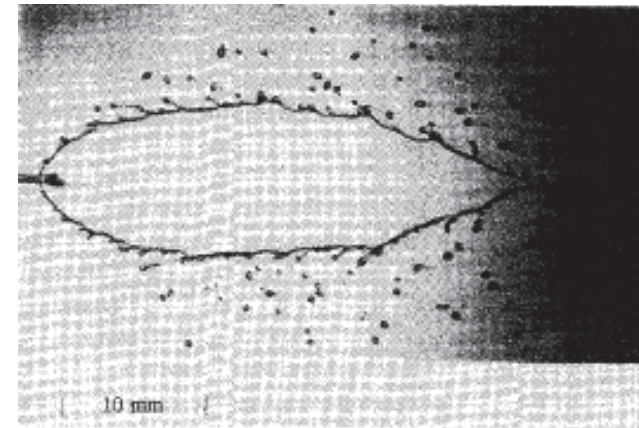
Low jet velocity (7.1 m/s) laminar impingement sheet photo (figure 4a from Ryan)

- Photos of turbulent and laminar liquid sheet deteriorations into droplets
- Images taken from the primary reference, Ryan et al.[1]

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- **Hydrazine, N_2H_4, and Hydrogen Peroxide, H_2O_2 were propellants considered**
  - **Represent current state of the art propellants used for spacecraft chemical propulsion applications**
  - **Significantly different from each other in physical properties and energy content**

Propellant	Liquid Property	Symbol	Value Range	Units	Value Constraints
N_2H_4	Coefficient of Viscosity, Dynamic	μ_L	9.736×10^{-4}	kg/(m-s)	$20^\circ C$
	Coefficient of Viscosity, Kinematic	ν_L	9.654×10^{-7}	m^2/s	$20^\circ C$
	Density	ρ_L	1.009×10^3	kg/m^3	$20^\circ C$
	Surface Tension	σ_L	6.850×10^{-4}	kg/s^2	$20^\circ C$
H_2O_2	Coefficient of Viscosity, Dynamic	μ_L	1.250×10^{-3}	kg/(m-s)	$20^\circ C$
	Coefficient of Viscosity, Kinematic	ν_L	8.621×10^{-7}	m^2/s	$20^\circ C$
	Density	ρ_L	1.450×10^3	kg/m^3	$20^\circ C$
	Surface Tension	σ_L	8.013×10^{-4}	kg/s^2	$20^\circ C$

Summary of propellant physical properties of hydrazine and hydrogen peroxide

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- Reaction Kinetics
  - Hydrazine, N_2H_4
    - $3 N_2H_4 \rightarrow 4 (1-X)NH_3 + (1+2X)N_2 + 6XH_2$
      - Where X represents the amount of ammonia, NH_3, dissociation
    - At 50% ammonia dissociation
      - $3 N_2H_4 \rightarrow 2NH_3 + 2N_2 + 3H_2$
      - T_C=1200-1300K
    - At 100% ammonia dissociation
      - $3 N_2H_4 \rightarrow 3N_2 + 6H_2$
      - T_C=874K
    - Increased ammonia dissociation leads to decreased gas decomposition temperature (decreased chamber temperature)
  - Hydrogen Peroxide, H_2O_2
    - $2 H_2O_2 \rightarrow 2 H_2O + O_2$
      - T_C=1274K
      - Presumes 100% concentration
      - Reduced concentration leads to decreased gas decomposition temperature (decreased chamber temperature)

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- **Weber (W_e) and Reynolds (R_e) Number**
  - The relationships from Ryan et al.[1] to determine liquid impingement sheet and atomized drop dimensions were bounded by Weber and Reynolds Number ranges of validity
    - $350 < W_e < 6{,}600$
    - $2{,}800 < R_e < 26{,}000$

- **Specific Impulse**
  - Specific impulse values were evaluated across a range of operating conditions
    - The vacuum operating condition with an expansion ratio of 50:1 was chosen
      - Showed the least variation across the chamber pressure region of interest

- **Discharge Coefficient**
  - Median value of 0.77 was used in calculations
    - Range of 0.732 to 0.809 resulted from calculations across the valid W_e and R_e range

- **Injector Orientation**
  - Impingement half angle, θ, of 40°, was chosen for calculations

- **Impingement Sheet Dimensions**
  - Angular displacement, ϕ, from the impingement point on the liquid sheet was presumed to be 0°
    - The item of interest where this is relevant was the impingement sheet length, which would be at $\phi = 0^o$

- **Droplet Formation, Size Distribution, and Decomposition**
  - **The effects of secondary atomization were not considered**
    - **Eases computational complexity of the model**
  - **The droplets evolved from the atomization that will have the most impact on chamber length are those evolved from the very end of the impingement sheet**
    - **Anticipate these drops will be the largest since at the longitudinal end of the sheet the drop velocity will be the lowest**
      - **Lower sheet velocities result in larger droplet diameters**
  - **Decomposition process was considered to have been achieved at the point in time when the propellant droplet had transitioned form a liquid to vapor state**

- **Vapor Phase Thermal Conductivity**
  - **Vapor phase thermal conductivities were calculated by combining the sum of reaction product species by mol fraction presence**
  - **More complex methods exist to derive this quantity, set forth by Saxena[6] and Mason[7]**
  - **Hydrazine vapor phase conductivity data is not readily available, used a surrogate molecule- Methanol, CH_3OH**
    - **Hydrazine vapor is not stable in the temperature regimes the value is required from**
    - **Hydrogen peroxide data was attainable**

- **Ryan et al.[1]**
  - Empirical study that resulted in algorithms for estimating impingement sheet length and evolved droplet diameter

- **Lefebvre[5]**
  - Injector orifice estimation algorithms relating liquid properties to discharge coefficient

- **Turns[9]**
  - Evolved droplet transition time relations for liquid to vapor phase that consider environmental conditions

- **Sutton[11] and Hill et al.[12]**
  - Standard equations relating various aspects of rocket engine performance

- **Schmidt[2], Brown[3], *The Hydrogen Peroxide Handbook*[4], Svehla[8], and *The CRC Handbook of Chemistry and Physics*[10]**
  - Physical property information for propellants

- **Spalding[13], Anderson[14], Ibrahim[15], and Dombroski[16]**
  - Relevant citations from Ryan and Hill in regards to combustion chamber dimension estimation

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- **Operational conditions considered**
  - **3 Combustion chamber pressures considered**
    - **125, 250, and 500 psi**
  - **3 mass flow rate ratios considered**
    - **m'_{gg} is the fraction of propellant allocated to the decomposition/ignition device, stage 1**
    - **m'_{inj} is the fraction of propellant allocated to injection and atomization downstream, stage 2**
    - **m'_{gg} to m'_{inj} ratios are 1:3, 1:4, and 1:5**
  - **2 pressure "hardness" ratios considered**
    - **Ratio of liquid propellant feed pressure to chamber pressure**
    - **1.25 and 1.75**
- **Indexing used to track each case through calculations**
  - **Combustion chamber pressure.Mass flow rate ratio.Hardness ratio**
  - **Shown in table**

Index	Pc (psi)	m' Ratio	hardness ratio
1.1.1	125	0.33	1.25
1.2.1	125	0.25	1.25
1.3.1	125	0.20	1.25
1.1.2	125	0.33	1.75
1.2.2	125	0.25	1.75
1.3.2	125	0.20	1.75
2.1.1	250	0.33	1.25
2.2.1	250	0.25	1.25
2.3.1	250	0.20	1.25
2.1.2	250	0.33	1.75
2.2.2	250	0.25	1.75
2.3.2	250	0.20	1.75
3.1.1	500	0.33	1.25
3.2.1	500	0.25	1.25
3.3.1	500	0.20	1.25
3.1.2	500	0.33	1.75
3.2.2	500	0.25	1.75
3.3.2	500	0.20	1.75

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General Algorithm-Valid Cases

- Injector discharge coefficients were first calculated using relations from Lefebvre[5] based on the range of validity for R_e from Ryan et al.[1]

$$C_{Dmax}=0.827-0.0085 \frac{l_o}{d_o}$$

$$\frac{1}{C_D} = \frac{1}{C_{Dmax}} + \frac{20}{R_e}(1+2.25 \frac{l_o}{d_o})$$

- Total mass flow rate (m'_{total}) derived from thrust (F_T) and specific impulse (I_{sp})

$$m'_{total} = \frac{F_T}{I_{sp}g_o}$$

- Mass flow rate of propellants through the injectors (m'_{inj}) derived from flow rate ratios

$$m'_{inj} = \frac{m'_{total}(1 - \frac{m'_{gg}}{m'_{inj}})}{\# \text{ of injectors}}$$

General Algorithm-Valid Cases

- Injector orifice dimensions (A_o, d_o) derived from injector mass flow rates, discharge coefficient (C_D), propellant density (ρ_L), and pressure drop (ΔP)

$$A_o = \frac{\dot{m}_{inj}}{C_D\sqrt{2\rho\Delta P}} \qquad\qquad d_o = 2\sqrt{\frac{A_o}{\pi}}$$

- W_e and R_e calculated from injection velocity (U_{inj}, derived from $\dot{m}'_{inj}$), orifice diameter, propellant density, and propellant viscosity (μ_L) and surface tension (σ_L)
    - Cross check ranges of validity, per Ryan et al.[1]

$$U_{inj} = \frac{\dot{m}_{inj}}{\rho_L A_o} \qquad\qquad W_e = \frac{\rho_L U_{inj}^2 d_o}{\sigma_L} \qquad\qquad R_e = \frac{\rho_L U_{inj} d_o}{\mu_L}$$

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General Algorithm-Chamber Environment

- Calculate specific heat ratio (γ) of the reaction products as a function theoretical decomposition/combustion temperatures from tabular data and ideal gas relations on mol fraction basis

$$\gamma = \frac{c_p}{c_v} \qquad\qquad R_U = c_p - c_v \qquad\qquad \gamma = \frac{\frac{c_p}{R_U}}{(\frac{c_p}{R_U} - 1)}$$

$$y_i = \frac{n_i}{n_T} \qquad\qquad \gamma_{mix}(T) = \frac{\Sigma y_i \frac{c_p(T)}{R_U}}{\Sigma y_i \frac{c_p(T)}{R_U} - 1}$$

- Calculate chamber gas density (ρ_C) based on chamber pressure (P_C) and Temperature (T_C) using ideal gas relations

$$\rho_c = \frac{P_c}{R_{spec} T_c}$$

- Calculate chamber gas to propellant liquid density ratio (S)

$$S = \frac{\rho_c}{\rho_L}$$

General Algorithm-Impingement Sheet and Drop Dimensions

- Calculate sheet velocity (U_S)

$$U_s = U_{inj} \cos(\theta)$$

- Calculate wave number (k_m) from chamber gas density, impingement sheet velocity, and surface tension

$$k_m = \frac{\rho_c U_s^2}{2\sigma}$$

- Calculate impingement sheet length (r_b) from orifice diameter, chamber gas to liquid propellant density ratio, and Weber number

$$r_b = \frac{d_o}{2(14.2 S^{\frac{-2}{3}} W_e^{\frac{-1}{3}})}$$

- Calculate sheet thickness (h) from orifice diameter, impingement sheet half angle (θ), sheet angular displacement (ϕ), and impingement sheet length

$$h = \frac{d_o^2 \sin^3\theta}{4 r_b (1 - \cos\phi\cos\theta)^2}$$

General Algorithm-Impingement Sheet and Drop Dimensions

- Calculate liquid sheet maximum growth rate factor ($\beta_{i,m}$) from kinematic viscosity (ν_L), wave number, chamber gas density, sheet velocity, surface tensions, propellant liquid density, and sheet thickness

$$\beta_{i,m} = \frac{\nu_L k_m^2}{2}\left(-1 + \sqrt{1 + \frac{8(\rho_c k_m U_S^2 - \sigma_L k_m^2)}{\nu_L^2 k_m^4 \rho_L h}}\right)$$

- Calculate drop diameter (d_D) from orifice diameter, sheet velocity, Weber number, chamber gas to liquid propellant density ratio, sheet length, and liquid sheet maximum growth rate factor

$$\frac{d_D}{d_o} = \left[\frac{2.62}{\frac{\beta_{i,m}}{U_s} r_b}\right]^{\frac{1}{3}} s^{\frac{-1}{6}} [w_c f(\theta)]^{\frac{-1}{3}} \qquad f(\theta) = \frac{(1-\cos\theta)^2}{\sin^3\theta}$$

General Algorithm-Droplet Evaporation Quantities

- Calculate chamber environment thermal conductivity (k_{inf}) from tabular data and mol fraction for reaction products

$$k_{inf} = \Sigma y_i k_i(T_{bar})$$

- Calculate median chamber temperature (T_{bar}) from propellant boiling point (T_{boil}) and chamber temperature

$$T_{bar} = \frac{(T_c + T_{boil})}{2}$$

- Calculate overall chamber gas phase thermal conductivity (k_g) from propellant vapor phase thermal conductivity (k_F) and chamber environmental thermal conductivity

$$k_g = 0.4 k_F (@\ T_{bar}) + 0.6 k_{inf} (@\ T_{bar})$$

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General Algorithm-Droplet Evaporation Quantities

- Calculate Spalding number (B_q) from specific heat at constant pressure for gas phase (c_{pg}), chamber temperature, propellant boil point, and latent heat of vaporization (h_{fg})
  - ratio of heat capacity as a function of the temperature difference between the environment and propellant boil point to the latent heat of vaporization

$$B_q = \frac{c_{pg}(T_c - T_{boil})}{h_{fg}}$$

- Calculate overall evaporation constant (K) from the overall chamber gas phase thermal conductivity, Spalding number, propellant liquid density, and specific heat at constant pressure for gas phase

$$K = \frac{8k_g}{\rho_L\, c_{pg}} \ln(B_q + 1)$$

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General Algorithm-Chamber and Throat Diameter

- Calculate sonic throat area (A*) from specific heat ratio, propellant mass flow rate, chamber pressure and temperature

$$\frac{\dot{m}_T}{A^*} = \frac{P_c}{\sqrt{R_{spec} T_c}} \sqrt{\gamma} (\frac{2}{\gamma+1})^{\frac{\gamma+1}{2(\gamma-1)}}$$

- Calculate chamber cross sectional area (A$_{chamber}$) from sonic throat area, chamber mach number (M, presumed to be 0.1), and specific heat ratio

$$\frac{A_{chamber}}{A^*} = \frac{1}{M} [\frac{2}{\gamma+1} (1+\frac{\gamma-1}{2} M^2)]^{\frac{\gamma+1}{2(\gamma-1)}}$$

- Calculate chamber diameter (D$_{chamber}$) from chamber cross sectional area

$$D_{chamber} = 2\sqrt{\frac{A_{chamber}}{\pi}}$$

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General Algorithm-Chamber Length

- **Calculate drop evaporation time (t_D) from drop diameter and evaporation constant**

$$t_D = \frac{d_D^2}{K}$$

- **Calculate drop distance traveled (L_D) from drop evaporation time and sheet velocity**
  - **Drop velocity is presumed equal to sheet velocity**

$$L_D = \frac{t_D}{U_S}$$

- **Calculate chamber length required (x_j) for impingement stream from chamber diameter and impingement half angle**

$$x_j = D_{chamber} \frac{\cos\theta}{\sin\theta}$$

- **Sum the impingement stream distance, impingement sheet length, and drop distance traveled to estimate required chamber length for a given configuration**

$$L_T = x_j + \tau_b + L_D$$

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- **For hydrazine, 6 cases did not meet the requirements of the relationships set forth by Ryan et al.[1]**
  - **Case 2.1.2-2.3.2 and 3.1.2-3.3.2**
    - **W_e exceeded upper boundary**
    - **Injection velocities were highest of cases considered**
      - **U_{inj} >32 m/s**
      - **Smaller d_o values relative to Ryan and increasing P_C, push increase in U_{inj}**
      - **Ryan's highest U_{inj} was 18.5 m/s**
      - **Lowest N_2H_4 case values was 15.9 m/s-all others exceeded**
      - **ρ_L to σ_L value of N_2H_4 lower than H_2O, however, substantially increased U_{inj} drove W_e values out of range**

N_2H_4 @ 5 lb$_f$: We as a function of U_{inj}
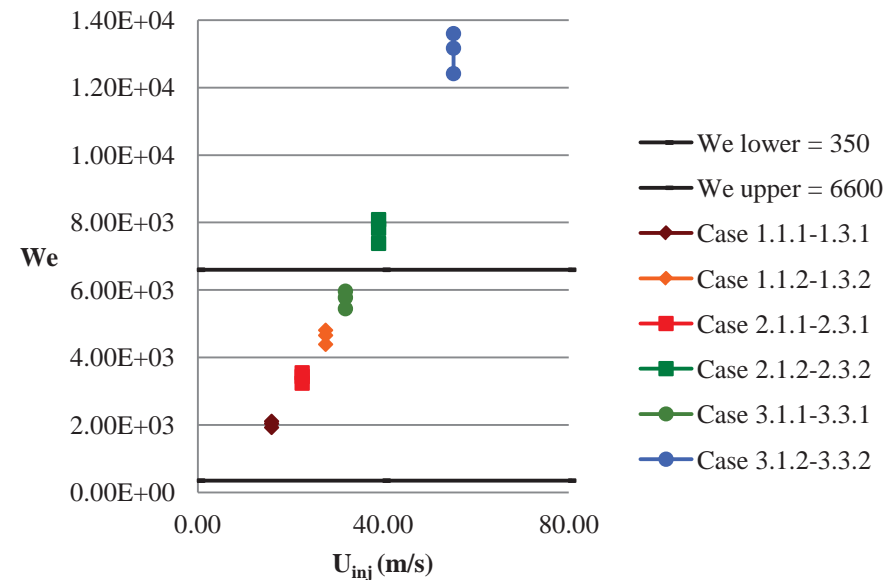
- **All cases met R_e requirement**

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- For hydrogen peroxide, 12 cases did not meet the requirements of the relationships set forth by Ryan et al.[1]
  - Case 1.1.2-1.3.2, 2.1.2-2.3.2, 3.1.1-3.3.1 and 3.1.2-3.3.2
    - W_e exceeded upper boundary
    - Injection velocities were highest of cases considered
      - $U_{inj} > 27$ m/s
      - Smaller d_o relative to Ryan and increasing P_C push increase in U_{inj}
      - Lowest H_2O_2 case value was 19.1 m/s-greater than Ryan's highest value
      - Combination of increased ρ_L to σ_L value of H_2O_2 relative H_2O & increased U_{inj} drove W_e values out of range

- All cases met R_e requirement

H_2O_2 @ 5 lb_f: We as a function of U_{inj}
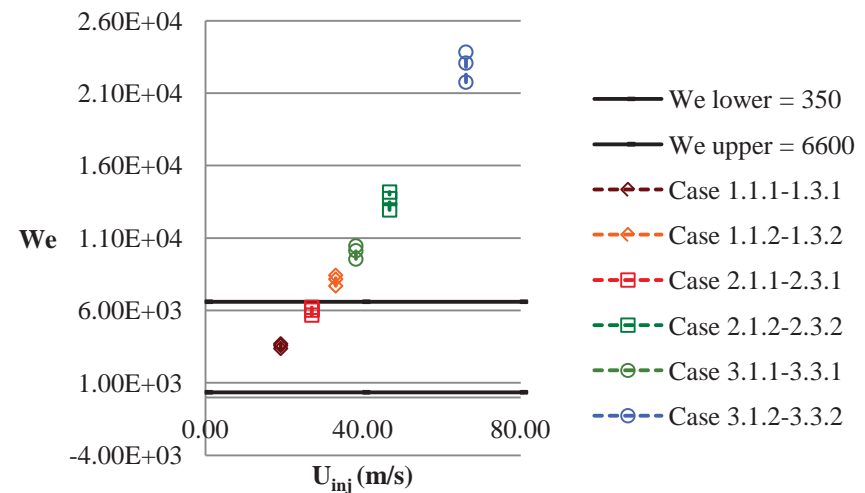
——	We lower = 350
——	We upper = 6600
--◇--	Case 1.1.1-1.3.1
--◇--	Case 1.1.2-1.3.2
--▫--	Case 2.1.1-2.3.1
--▫--	Case 2.1.2-2.3.2
--○--	Case 3.1.1-3.3.1
--○--	Case 3.1.2-3.3.2

- **Relative to Ryan et al.[1], the values of impingement sheet length to injector orifice diameter are low**
  - Closest agreement observed for the turbulent cases of empirical data
    - These study points had the lowest injection velocities
- **Larger values of calculated U_{inj} in the study drive increased We & rb values relative to the model of Ryan**
  - Case 1.1.1-1.3.1 closest in agreement
  - Increasing W_e of study does not overcome effect of decreased r_b to d_o ratio
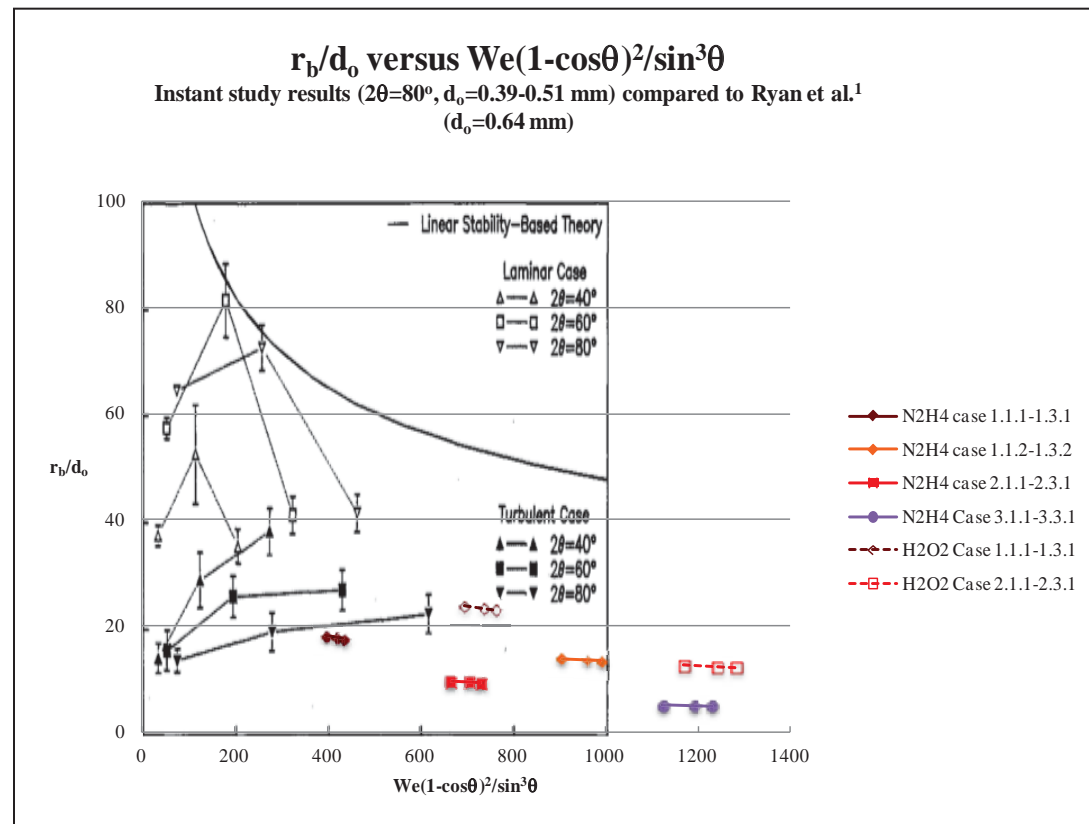
r_b/d_o versus $We(1-\cos\theta)^2/\sin^3\theta$
Instant study results ($2\theta=80^o$, d_o=0.39-0.51 mm) compared to Ryan et al.[1]
(d_o=0.64 mm)

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- **Relative to Ryan et al.[1], the values of evolved droplet to injector orifice diameter are low**
  - Appear to agree in trend
- **Hydrazine's physical property values are closer to water (liquid Ryan used) than hydrogen peroxide**
- **Instant study calculated droplet to orifice diameter ratio appears to be about a factor of 3 less than those of Ryan**
- **The value of $\int \beta_{i,m} dt \sim 26$ for the instant study, calculated with physical properties**
- **Smaller d_o study values resulted in smaller values of d_D, pushing study values of their ratio below those of Ryan**

d_D/d_o versus $We(1-\cos\theta)^2/\sin^3\theta$
Instant study results compared to Figure 8 of Ryan et al.[1]
$2\theta=80°$, $d_o=0.39-0.51$ mm
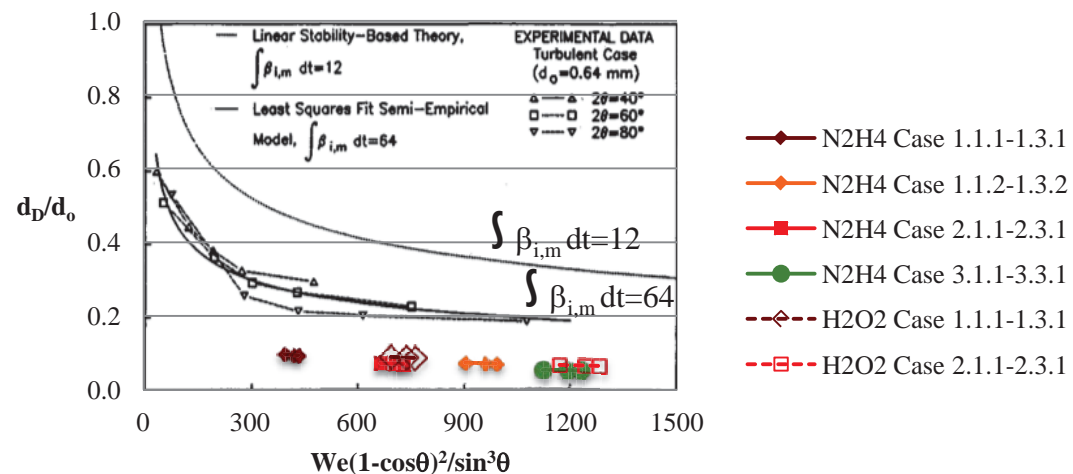
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- Chamber dimensions decrease as the chamber pressure increases
  - For a fixed thrust level this is sensible since the same amount of high temperature gas is evolved
    - The only path to increased chamber pressure is decreased volume

- Hydrogen peroxide values are slightly larger than those for hydrazine
  - Lower specific impulse increases the mass flow rate required
  - Has a higher decomposition temperature
  - Both of these factors drive increased values relative to hydrazine

D*, D as function of P_c & γ values for N_2H_4 & H_2O_2
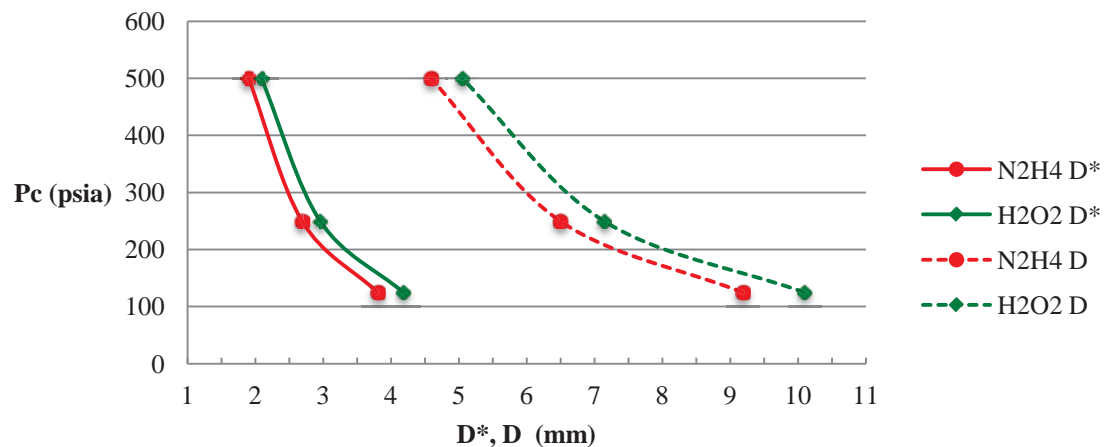
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- Increasing chamber pressure shows a decreasing chamber length result
  - Consistent with diameter and throat calculations

- Decreasing 1st stage mass flow (increasing second stage mass flow rate) was not a driver
  - Holding C_D constant held the injection velocity constant, adjusted the orifice dimension (increased with increasing mass flow to the second stage)

- Increasing hardness ratio decreases chamber length
  - Increases injection velocity

N_2H_4 Chamber Dimensions
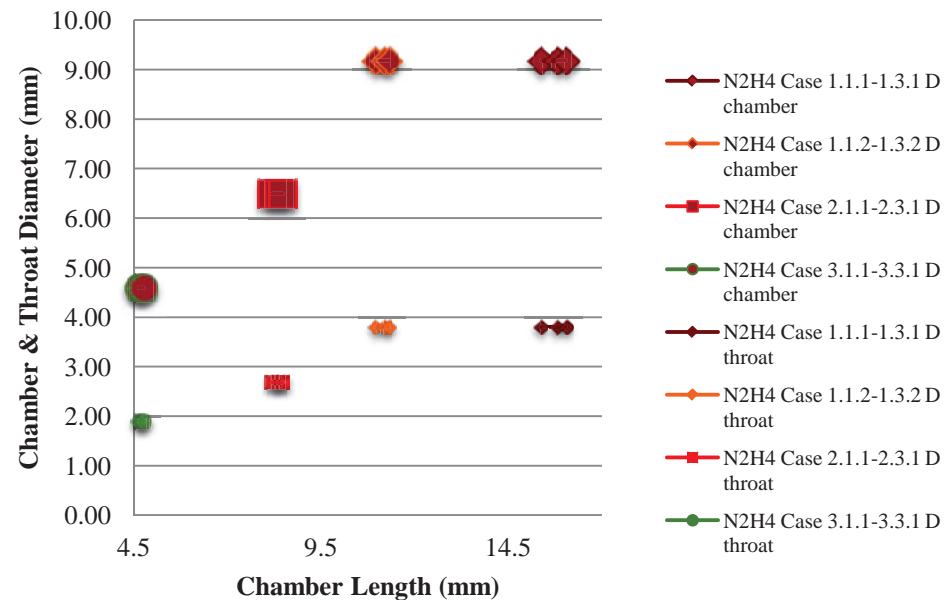
Chamber & Throat Diameter (mm) vs Chamber Length (mm)

Legend:
- N2H4 Case 1.1.1-1.3.1 D chamber
- N2H4 Case 1.1.2-1.3.2 D chamber
- N2H4 Case 2.1.1-2.3.1 D chamber
- N2H4 Case 3.1.1-3.3.1 D chamber
- N2H4 Case 1.1.1-1.3.1 D throat
- N2H4 Case 1.1.2-1.3.2 D throat
- N2H4 Case 2.1.1-2.3.1 D throat
- N2H4 Case 3.1.1-3.3.1 D throat

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- Similar trends as with hydrazine

- Increasing chamber pressure shows a decreasing chamber length result
  - Consistent with diameter and throat calculations

- Increasing hardness ratio decreases chamber length
  - Increases injection velocity

- Resulting overall chamber length is greater than that of hydrazine
  - Greater relative injection velocities

H$_2$O$_2$ Chamber Dimensions
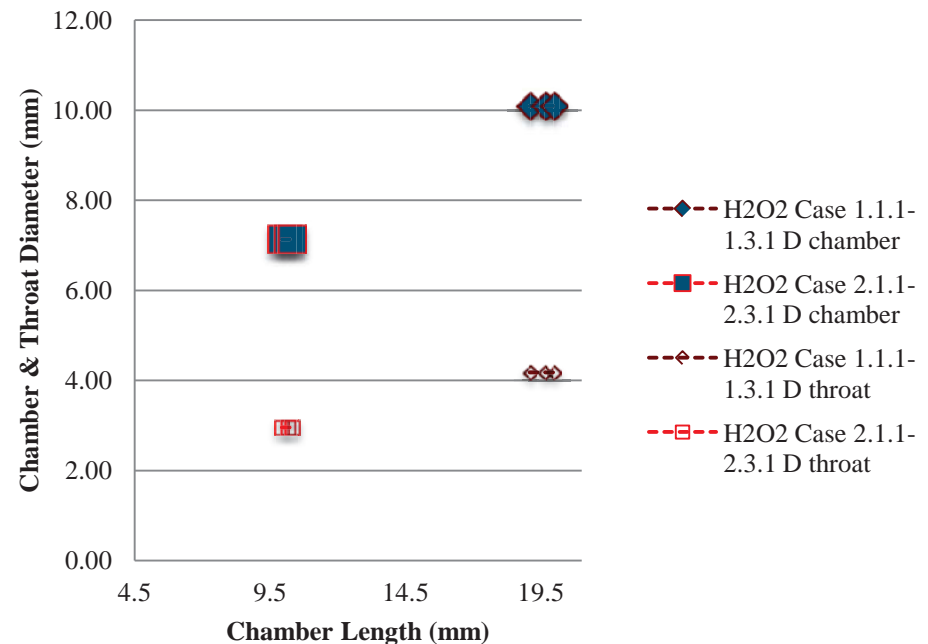
Legend:
- H2O2 Case 1.1.1-1.3.1 D chamber
- H2O2 Case 2.1.1-2.3.1 D chamber
- H2O2 Case 1.1.1-1.3.1 D throat
- H2O2 Case 2.1.1-2.3.1 D throat

X-axis: Chamber Length (mm)
Y-axis: Chamber & Throat Diameter (mm)

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- **Contrasting hydrogen peroxide to hydrazine, an increased chamber volume is required for an equivalent operating condition**
  - **Most likely driven by the decreased energy content which drives increased propellant mass flow rates**
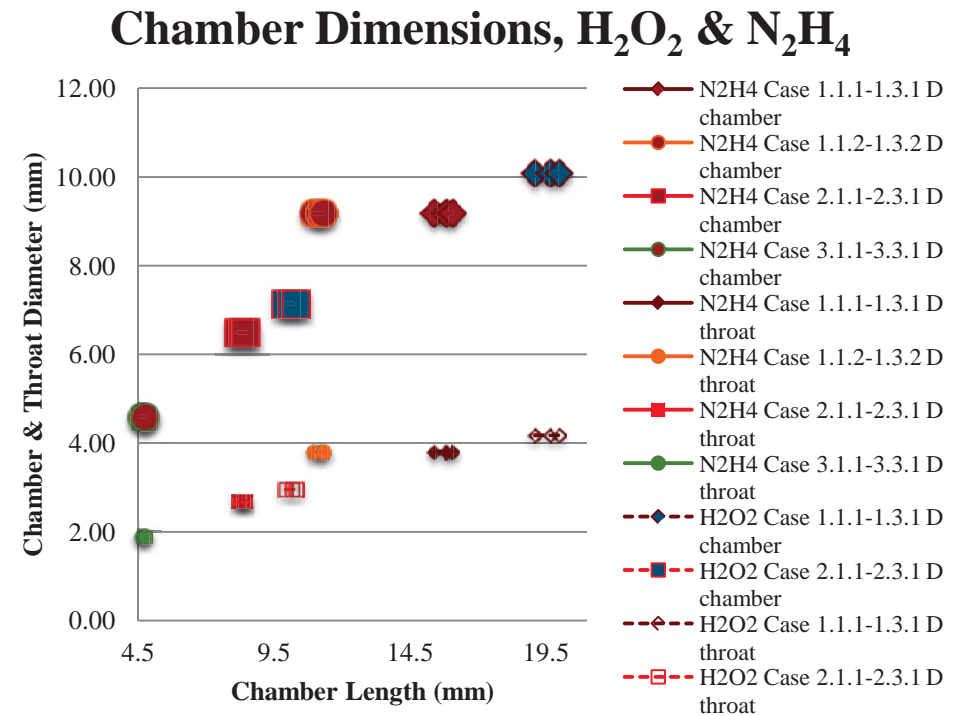
Chamber Dimensions, H_2O_2 & N_2H_4

Legend:
- N2H4 Case 1.1.1-1.3.1 D chamber
- N2H4 Case 1.1.2-1.3.2 D chamber
- N2H4 Case 2.1.1-2.3.1 D chamber
- N2H4 Case 3.1.1-3.3.1 D chamber
- N2H4 Case 1.1.1-1.3.1 D throat
- N2H4 Case 1.1.2-1.3.2 D throat
- N2H4 Case 2.1.1-2.3.1 D throat
- N2H4 Case 3.1.1-3.3.1 D throat
- H2O2 Case 1.1.1-1.3.1 D chamber
- H2O2 Case 2.1.1-2.3.1 D chamber
- H2O2 Case 1.1.1-1.3.1 D throat
- H2O2 Case 2.1.1-2.3.1 D throat

Axis labels: Chamber & Throat Diameter (mm) vs Chamber Length (mm)

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- Performed study to develop first iteration chamber dimension estimates based upon propellant physical properties
  - Chamber dimensions derived from atomization characteristics of propellants of interest
  - Performed relative comparison of results to published empirical data
    - Results had small overlap with published data

- Increasing chamber pressure and hardness ratio decrease the overall chamber dimensions for a given thrust level

- For the propellants considered, energy content appears to have a greater impact on the chamber dimensions than the physical properties
  - Injection velocity appeared to be a greater contributor to We number than physical properties
  - Increasing We for a given chamber pressure increases chamber length required to achieve liquid to vapor transition of droplets

- Relative comparison with resulting engine dimensions from study difficult to compare to state of the art engines
  - Requires knowledge of injection parameters, generally held proprietary
  - By visual inspection, the dimensions are:
    - Small relative to state of the art monopropellant hydrazine & nitrogen tetra-oxide/hydrazine bipropellant engines for the same thrust level

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Notation	Definition
a	Curve fit polynomial constant
$A_{chamber}$	Chamber cross-sectional area
A*	Throat cross-sectional area
A_o	Injector orifice cross-sectional area
B_q	Spalding or transfer number, based on heat transfer considerations only
c_{pg}	Specific heat at constant pressure of gas phase
C_D	Discharge coefficient
C_{Dmax}	Discharge coefficient value attained at Re > 10,000
CH_3OH	Methonal
c_p	Specific heat at constant pressure
c_v	Specific heat at constant volume
$D_{chamber}$	Chamber diameter
D*	Throat diameter
d_D	Droplet diameter
d_o	Injector orifice diameter
d_{jet}	Impinging liquid propellant jet diameter
F_T	Thrust force
g_o	Gravity
h	Liquid propellant sheet thickness
H	Hydrogen, monatomic

Notation	Definition
H_2	Hydrogen, diatomic
H_2O	Water
H_2O_2	Hydrogen Peroxide
h_{fg}	Latent heat of vaporization
Isp	Specific impulse
K	Evaporation constant
k_F	Propellant gas phase thermal conductivity
k_g	Environment gas phase thermal conductivity
k_m	Wave number for the most unstable wave
k_{inf}	Gas generator combustion product gas phase thermal conductivity
L_D	Distance traveled by droplet until fully evaporated
L_T	Total chamber distance required for injection, atomization and evaporation of liquid propellant
l_o	Injector tube length
M	Mach number
m'	Mass flow rate of liquid propellant
MeOH	Methonal
m'_{gg}	Gas generator mass flow rate of liquid propellant
m'_{gg}/m'_{inj}	Ratio of mass flow rate of liquid propellant injected through the gas generator to the that injected downstream
m'_{inj}	Injected mass flow rate of injected liquid propellant
m'_T	Total mass flow rate of liquid propellants injected into the thruster, derived from specific impulse and thrust requirement.
MSDS	Material Safety Data sheet
MW	Molecular weight

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N	Nitrogen, monatomic
N_2	Nitrogen, diatomic
N_2H_4	Hydrazine
n_i	Mol fraction for a particular species
n_T	Total mols of all species in a reaction
O	Oxygen, monatomic
O_2	Oxygen, diatomic
P_c	Chamber pressure
P_f	Feed pressure
$P_{f/c}$	Ratio of feed to chamber pressure, other wise referred to as "hardness" ratio
r_b	Radial distance from impingement point where liquid sheet break up into ligaments occurs
R, R_u	Universal gas constant
R_{spec}	Universal gas constant divided by the MW of the gas of interest
R_e	Reynolds number, ratio of inertial forces to viscous forces
S	Ratio of chamber gas density to liquid propellant density
SL	Sea Level
T	Temperature
T_{bar}	Average temperature of the free stream environment and the liquid propellant boiling point
T_{boil}	Boiling point temperature of liquid propellants
T_c	Chamber (combustion product) temperature
T_{inf}	Free stream environment temperature

$\Delta T_{inf\text{-}boil}$	The difference between the free stream environment temperature and the liquid propellant boiling point
U_{inj}, U_j	Injected liquid propellant jet velocity
U_s	Velocity of liquid in sheet resulting from impingement of injected liquid jets
Vac	Vacuum
W_e	Weber number, ratio of inertia to surface tension
X	Percentage of ammonia dissociation in hydrazine decomposition reaction
x_j	Horizontal length component of liquid jet within chamber
y_i	Molar mass fraction,
$\beta_{i,m}$	Liquid sheet disturbance maximum growth rate
γ	Specific heat ratio
γ_{mix}	Specific heat ratio for a particular molecule
μ_L	Dynamic viscosity coefficient
ν_L	Kinematic viscosity coefficient
ϕ	Angle relative to centerline of the liquid sheet formed from impingement of liquid propellant jets
ρ_L	Liquid propellant density
ρ_C	Chamber gas phase density
σ_L	Surface tension
θ	Impingement half angle

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